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(54) **Method and apparatus for noise-quieting in brushless DC motors**

(57) A circuit for driving a brushless DC motor which reduces the interaction of axial forces between the motor windings (W_1, W_2) and the permanent magnet rotor. The circuit provides feedback of the back EMF developed by the motor winding (W_2) from which power is being removed to the motor winding (W_1) to which power is being applied.

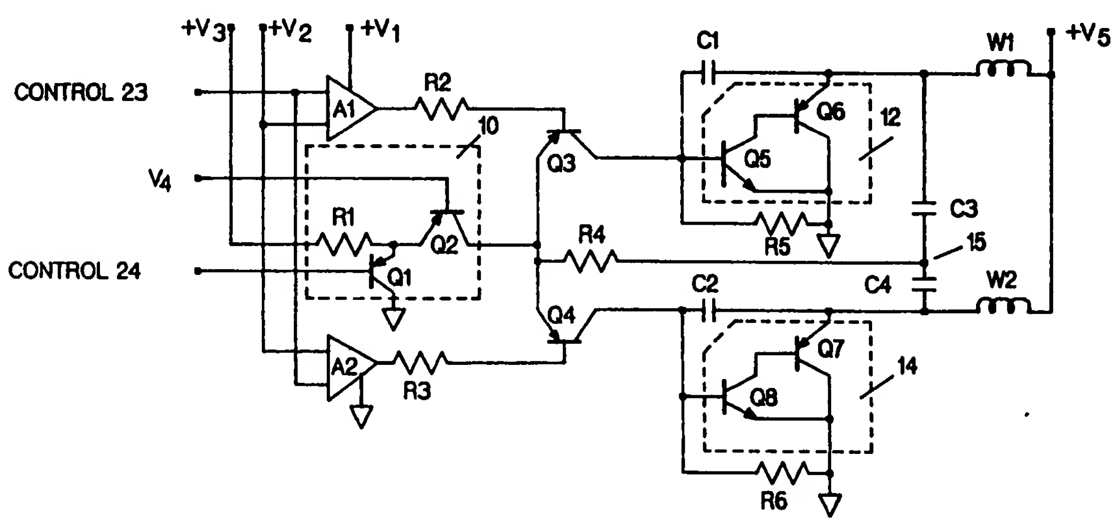

FIGURE 1

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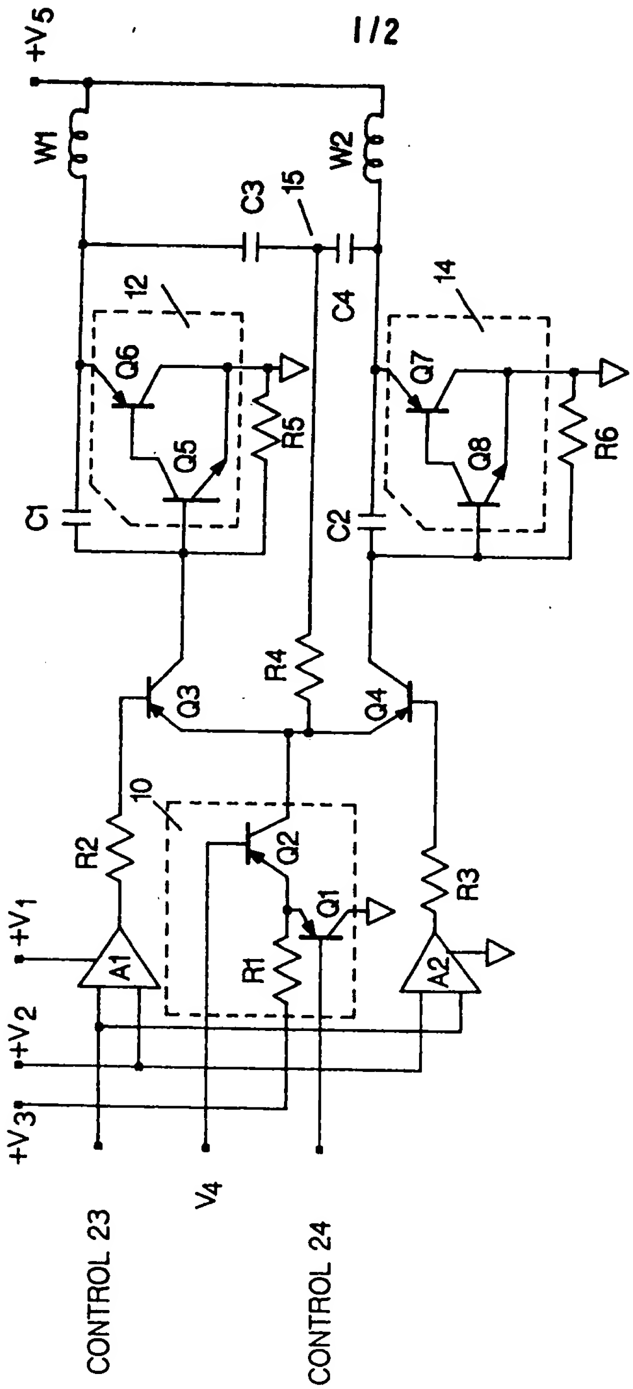

+V5
W1
W2
C3
15
C4
12
14
Q6
Q5
Q7
Q8
R5
R6
C1
C2
R4
Q3
Q4
10
R2
Q2
Q1
R1
R3
A1
A2
+V1
+V2
+V3
V4
CONTROL 23
CONTROL 24

FIGURE 1

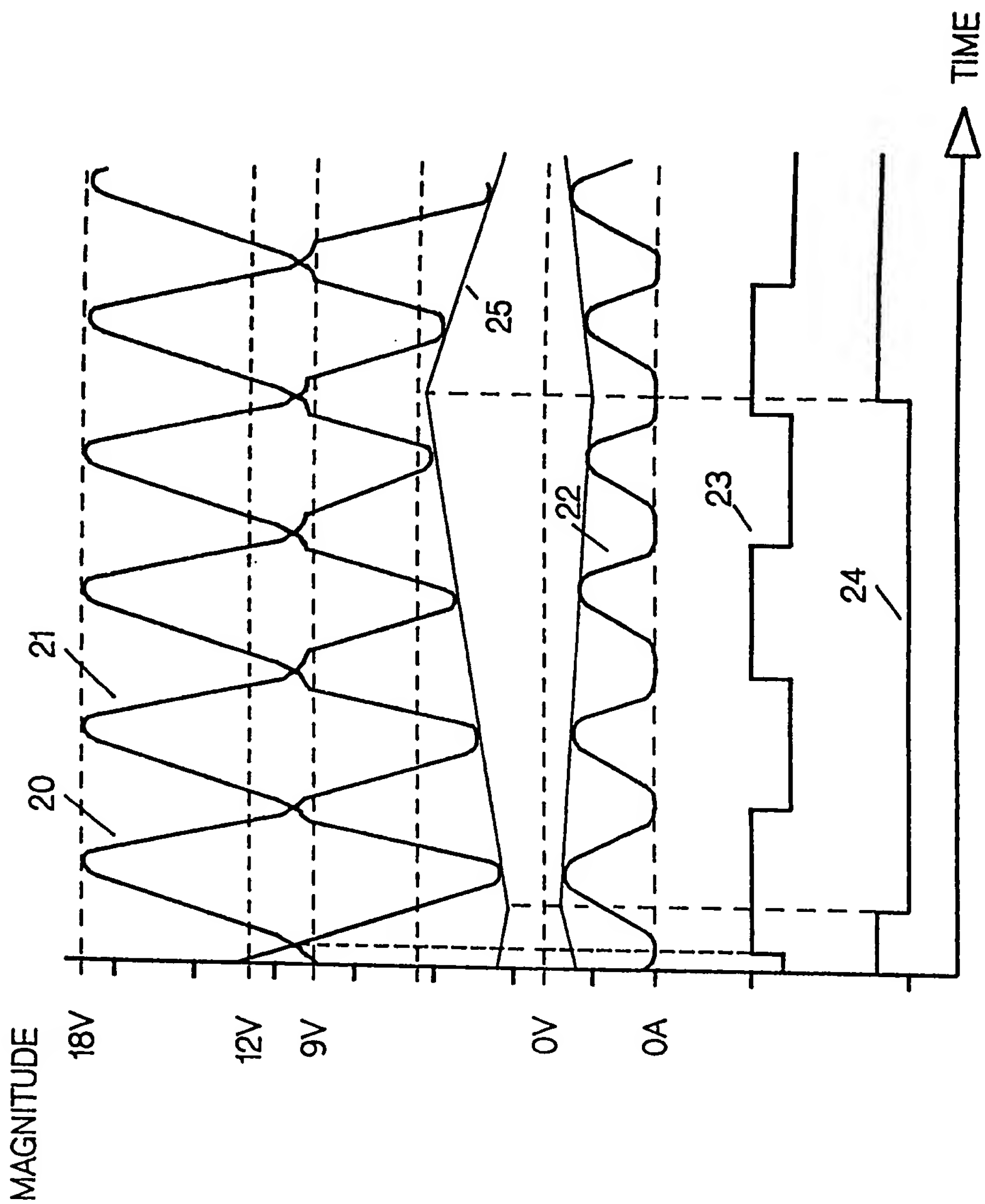

FIGURE 2

SPECIFICATION

Method and apparatus f r noise-qui ting in brushless DC motors

The present invention relates to electronic circuitry for driving brushless DC motors. In particular, this invention provides a method and circuitry for quieting audio frequency noise produced by such motors when driven by conventional circuit configurations.

At least one source of audio frequency noise produced by brushless DC motors is caused by the interaction of forces set up between the motor windings and the permanent magnet rotor when driven by conventional circuitry. Typically, convention circuitry comprises power transistors which alternately draw current through the motor windings from a power supply on demand derived from a signal produced by a Hall effect device as the rotor rotates. This scheme simply draws required current through the windings to control motor speed.

According to one aspect of the present invention, there is provided apparatus for driving a brushless DC motor having a plurality of windings, said apparatus comprising driver means for sequentially applying drive current to the windings of the motor; and feedback means, coupled to the driver means, for applying the back EMF developed by the motor winding from which drive current is being removed to the motor winding to which drive current is being applied.

According to another aspect of the present invention, there is provided a method for driving a brushless DC motor having a plurality of windings, said method comprising the steps of alternately applying drive current to the windings of the motor; and applying the back EMF developed by the motor winding from which drive current is being removed to the motor winding to which drive current is being applied.

In the accompanying drawings:–

Figure 1 is a schematic diagram of the motor driver constructed according to the principles of the present invention; and

Figure 2 is a timing diagram of control and drive signals for the motor driver circuit of Fig. 1.

The spindle motor driver circuit of Fig. 1 energizes motor windings W_1 and W_2 in response to signals produced by a Hall effect device and a microprocessor. More particularly, a first cyclic control waveform 23 determines which winding W_1 or W_2 is energized on th basis of the rotational position of the rotor as sens d by the Hall effect device (not shown); a second cyclic control waveform 24, of low r frequency than the control waveform 23, is used to slowly increase and decrease the average level of energization of the windings W_1 and W_2 in order to assist stability of the motor speed. Both c ntrol waveforms 23,24 are generated by a controlling micropr cessor (not sh wn).

A current source 10 c mprises Q_1, Q_2 and R_1. The base of Q_2 is coupled to reference voltage V_4 and the base of Q_1 is connected t control signal 24. The emitters of transistors Q_1 and Q_2 are commonly coupled to reference voltage V_3 through resistor R_1.

Referring to Fig. 2, when control signal 24 is high Q_1 is off (i.e. cut off) and Q_2 is on (i.e. active). The voltage at the emitters of Q_1 and Q_2 is approximately 4 volts. In the present example, approximately 4.2 milliamps of current is available from the collector of Q_2.

When control signal 24 is low Q_1 is turned on as current flows from its base. As current flows through R_1, Q_2 becomes back-biased and is turned off.

The motor winding to which power is supplied is selected by comparators A_1 and A_2. When control signal 23 is low, motor winding W_1 is selected by comparator A_1. Conversely, motor winding W_2 is selected by comparator A_2 when control signal 23 is high.

Transistor Q_3 functions as a switch when the output of comparator A_1 is low. Base current drawn through R_2 causes Q_3 to saturate thus providing short circuit from its emitter to collector. Transistor Q_4 functions in the same manner in response to low voltage at the output of comparator A_2.

Transistors Q_5 and Q_6 operate as Darlington pair 12 to provide power to motor winding W_1. Thus substantial drive current can be provided in response to minimal control current applied to the base of Q_5. Capacitors C_1 and C_3 and resistor R_5 are used to control the rate at which power is applied to the motor windings and to provide feedback of back EMF produced by de-energized motor winding W_2 for reducing audio frequency noise. An identical circuit comprising Darlington pair 14 (i.e. transistors Q_7 and Q_8), capacitors C_2, C_4 and resistor R_6 is provided to drive motor winding W_2.

Referring again to Fig. 2, waveforms 20 and 21 respectively represent the voltage drive waveforms for the windings W_1 and W_2 (these voltages being those present at the node between winding W_1 and capacitor C_3 and at the node between winding W_2 and capacitor C_4 respectively).

When control signal 24 is low, current source 10 is off. Assuming motor winding W_2 was energized just prior to control signal 24 changing from high to low state, minimum operating charge still xists in capacitor C_4. If control signal 23 is high so that comparator A_2 has caused Q_4 to turn on, capacitor C_4 then charges through resistor R_4 to the base of transistor Q_8. As capacitor C_4 charges toward the voltage level V_5, Darlington pair 14 is turned on and current flows in resistor R_6. Thus, the voltage at circuit nod 15 is fixed at

approximat ly 1 volt. Feedback from C_4 assures that the voltag remains fixed as long as Darlington pair 14 is not saturated.

The rate at which C_4 charges, and consequently the rate at which th energizati n of winding W_2 is reduced over several switching cycles, is substantially determined by the current flowing through R_8. The current into the base of Q_8 and into C_2 is negligible because of the high gain of Darlington pair 14.

If C_4 charged faster, the current flowing to ground through resistor R_8 would increase the base voltage of Q_8 thus turning it on more. If Q_8 is turned on harder, more power is applied to motor winding W_2 which increases the voltage drop across W_2 and forces the voltage at circuit node 15 to decrease. If the voltage at that node decreases, current through R_8 decreases, which in turn reduces the base voltage of Q_8.

With continuing reference to Figs. 1 and 2, when control signal 24 is high, current source 10 is turned on. If control signal 23 is also high, more power is applied to the motor winding at a rate primarily determined by the rate determined by C_4 discharging through R_4. Thus, the current from current source 10 is divided through resistor R_8, on the one hand, and R_4 on the other. The amount of current flowing through R_8 is determined by V_{be} of Q_8 divided by R_8. The balance of the current available from current source 10 charges capacitor C_4 through resistor R_4. At this time, the voltage at the C_4 R_4 node 15 is fixed at approximately 0.3 volts. By making the voltage at circuit node 15 different when power is applied to winding W_2 than when power is removed from winding W_2, the stability of motor speed is enhanced.

Capacitors C_3 and C_4 allow coupling from the winding which the circuit is not driving to the winding which the circuit is driving by fixing the voltage at circuit node 15. The back EMF generated in the winding not being driven is inverted and applied to the winding which is being driven during the middle of each phase of control signal 23. See for example, motor drive voltage 21 driving window W_2 during positive phase of control signal 23 shown in Fig. 2. Approximately 6 volts of back EMF is being added to motor winding W_2 from motor winding W_1 during the first full, positive phase of control signal 23.

Capacitors C_1 and C_2 control the rate at which power is switched between motor windings W_1 and W_2 (C_1, C_2 are much smaller in value than C_3, C_4). For example, when transistor Q_4 turns off and transistor Q_3 turns on in response to control signal 23 changing state, the Darlington pair 14 turns off at a rate determined by the discharge of capacitor C_2 through R_8. Thus, as voltage 21 ris s, motor driv voltag 20 decr ases at the same rat because capacitor C_4 provides coupling to circuit node 15. Thus, the voltag b ing removed fr m motor winding W_2 is transferred t mot r winding W_1 in a relatively sh rt period f time. Capacitors C_1 and C_2 also protect transist rs Q_6 and Q_7 from v ltage breakdown owing to high transient voltages produced by motor windings W_1 and W_2 if drive current 22 were reduced too rapidly when power is switched from one winding to the other.

Referring again to Fig. 2, drive current 22 is applied to motor winding in phase with driv voltages 20 and 21. Thus, current is switched from one motor winding to the other approximately coincident with a change of state of control signal 23.

As stated elsewhere in this specification, when control signal 24 is high, current source 10 provides current to transistors Q_3 and Q_4. Control signal 23 determines which path the current shall take. When control signal 23 is high, current flows through Q_4; when control signal 23 is low, current flows through Q_3. The source of control signal 23 is a Hall effect device which monitors the magnetic field of the rotor of the motor being driven to determine the appropriate winding to which power should be applied.

When control signal 23 is high and control signal 24 is low, current source 10 is turned off. When control signal 23 is high, Q_4 effectively connects capacitor C_4 to the base of transistor Q_8 via resistor R_4. Since no current is supplied by current source 10, Darlington pair 14 is turned off at a rate determined by the charging of capacitor C_4 through resistor R_8. The base current required by transistor Q_8 and the charging current of capacitor C_2 has negligible effect on the turn off rate of Darlington pair 14.

Capacitors C_3 and C_4 integrate current from current source 10 between the rapid phase transitions of control signal 24 to a slowly varying drive level 25 at the motor winding being driven. Thus, when control signal 24 is low, voltage drive level 25 linearly decreases; when control signal 24 is high, voltage drive level 25 linearly decreases and increases in phase with voltage drive level 25. It should be noted that voltage drive level 25 decreases as the negative magnitude of voltage 20 and 21 decreases.

The rate of integration by capacitors C_3 and C_4 is controlled by the current flowing through resistor R_4 which current is the difference between the current from current source 10 and the current flowing through resistor R_5 or R_8. Current flows from current source 10 when control signal 24 is high. Thus, the voltage on capacitors C_3 or C_4 charges at a rate determined by the current through resistor R_4. Since the voltage at circuit node 15 is fixed by feedback from Darlington pair 12 or 14, voltage drive level 25 varies linearly with int - gration of the current flowing through resistor R_4. When c ntrol signal 24 is low, no current flows from current s urce 10 and the current

through resist r R_4 is equal to the current in r sist r R_5 or R_6.

Resistor R_4 helps stabilize the speed c ntrol loop by pr viding an immediate increase or decrease of the voltage at circuit node 15 as necessary to maintain constant level. The amount of such increase or decrease is determined by the difference between the current flowing through resistor R_4 from current source 10 in response to control signal 24 when it is high, and the current flowing through resistor R_4 to ground via resistor R_5 or resistor R_6 when control signal 24 is low.

Under ordinary load conditions, the drive current 22 of Fig. 2, effectively turns off at or near transitions of control signal 23. Since interaction of forces between the motor windings and the permanent magnet rotor are greatest during those transitions while is flowing in the motor windings, decreasing drive current 22 near such transitions substantially reduces those interacting forces and the resultant audio frequency noise.

When current is flowing in one motor winding at a transition of control signal 23, capacitor C_1 or C_2 controls the rate at which drive voltage is transferred to the other winding. In addition, by controlling the rate of turn off of the drive voltage, capacitor C_1 or C_2 prevents voltage breakdown of its respective Darling pair caused by the inductance of the motor winding. Thus, when transistor Q_4 turns off and transistor Q_3 turns on, Darlington pair 14 turns off at a rate determined by the discharge of capacitor C_2 through R_6.

In addition to ensuring stability of the speed regulation loop, R_4 regulates the flow of current from capacitors C_3 and C_4 which have been excessively charged during start up. During start up, power transistors Q_6 and Q_7 saturate, which drives circuit node 15 positive. Resistor R_4 maintains saturation of the power transistor which is applying power to a motor winding when the induced voltage, developed by the winding from which power is being removed, begins to decrease. Thus, resistor R_4 limits the discharge of capacitors C_3 and C_4 to asure effective start up of the motor.

CLAIMS

1. Apparatus for driving a brushless DC motor having a plurality of windings, said apparatus comprising:

driver means for sequentially applying drive current to the windings of the motor; and

feedback means, coupled to the driver means, for applying th back EMF developed by the motor winding from which drive current is being removed to the motor winding to which drive current is being appli d.

2. A method for driving a brushless DC motor having a plurality of windings, said method comprising the steps of:

alternately applying drive current to the windings of the motor; and

applying the back EMF developed by the motor winding from which drive current is being rem ved to the motor winding t which drive current is being applied.

3. Apparatus for driving a brushless DC motor, said apparatus being substantially as hereinbefore described with reference to the accompanying drawings.

4. A method of driving a brushless DC motor, said method being substantially as hereinbefore described with reference to the accompanying drawing.

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